

# Observing multiple stellar populations with FORS2@VLT

## Main sequence photometry in outer regions of NGC 6752, NGC 6397, and NGC 6121 (M 4).<sup>★</sup>

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### ABSTRACT

**Aims.** We present the photometric analysis of the external regions of three Galactic Globular Clusters: NGC 6121, NGC 6397 and NGC 6752. The main goal is the characterization of the multiple stellar populations along the main sequence (MS) and the study of the radial trend of the different populations hosted by the target clusters.

**Methods.** The data have been collected using FORS2 mounted at the ESO/VLT@UT1 telescope in *UBVI* filters. From these data sets we extracted high-accuracy photometry and constructed color-magnitude diagrams. We exploit appropriate combination of colors and magnitudes which are powerful tools to identify multiple stellar populations, like *B* versus *U – B* and *V* versus  $c_{U,B,I} = (U - B) - (B - I)$  CMDs.

**Results.** We confirm previous findings of a split MS in NGC 6752 and NGC 6121. Apart from the extreme case of  $\omega$  Centauri, this is the first detection of multiple MS from ground-based photometry. For NGC 6752 and NGC 6121 we compare the number ratio of the blue MS to the red MS in the cluster outskirts with the fraction of first and second generation stars measured in the central regions. There is no evidence for significant radial trend.

The MS of NGC 6397 is consistent with a simple stellar population. We propose that the lack of multiple sequences is due both to observational errors and to the limited sensitivity of *U, B, V, I* photometry to multiple stellar populations in metal-poor GCs.

Finally, we compute the helium abundance for the stellar populations hosted by NGC 6121 and NGC 6752, finding a mild ( $\Delta Y \sim 0.02$ ) difference between stars in the two sequences.

### 1. Introduction

Over the last years, the discovery that the color-magnitude diagrams (CMDs) of many globular clusters (GCs) are made of multiple sequences has provided overwhelming proof that these stellar systems have experienced a complex star-formation history. The evidence that GCs host multiple stellar populations has reawakened the interest on these objects both from the observational and the theoretical point of view.

Multiple sequences have been observed over all the CMD, from the main sequence (MS, e.g. Piotto et al. 2007) through the sub-giant branch (SGB, e.g. Piotto et al. 2012) and from the SGB to the red-giant branch (RGB, e.g. Marino et al. 2008) and even in the white-dwarf cooling sequence (Bellini et al. 2013a).

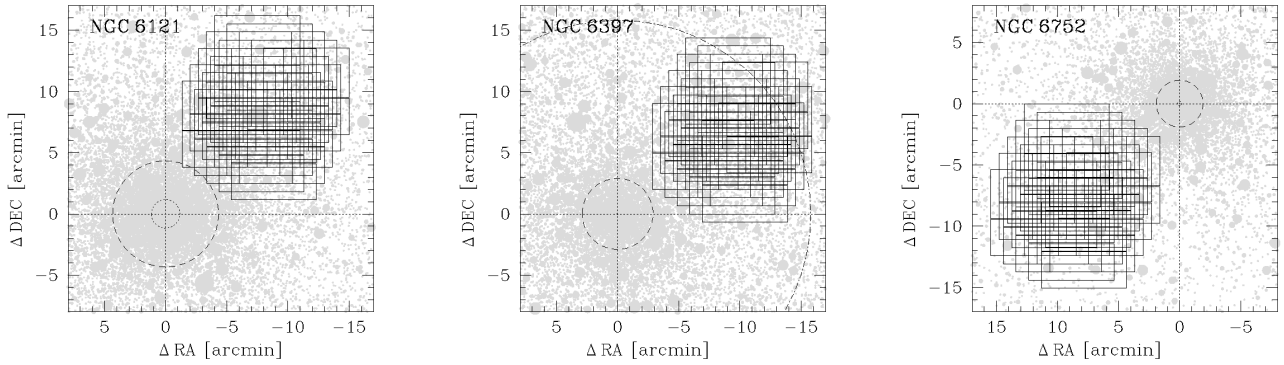
Multiple populations along the RGB have been widely studied in a large number of GCs (e.g. Yong et al. 2008, Lee et al. 2009, Monelli et al. 2013) by using photometry from both ground-based facilities and from the *Hubble Space Telescope* (*HST*). In contrast, with the remarkable exception of

$\omega$  Centauri (Sollima et al. 2007, Bellini et al. 2009b), the investigation of multiple MSs has been carried out with *HST* only (e.g. Bedin et al. 2004, Piotto et al. 2007, Milone et al. 2012a and references therein, Bellini et al. 2013b).

In this paper we will exploit the FOcal Reducer and low dispersion Spectrograph 2 (FORS2), mounted at the Very Large Telescope (VLT) of the European Southern Observatory (ESO) to obtain accurate *U, B, V, I* photometry of MS stars in the outskirts of three nearby GCs, namely NGC 6121 (M 4), NGC 6397, and NGC 6752, and study their stellar populations.

The paper is organized as follows: in Sect. 2 we provide an overview on the three GCs studied in this paper. The observations and the data reduction are described in Sect. 3. The CMDs are analyzed in Sect. 4, where we also show evidence of bimodal MSs for stars in the outskirts of NGC 6121 and NGC 6752 and calculate the fraction of stars in each MS. In Sect. 5 we study the radial distribution of stellar populations in NGC 6752 and NGC 6121. In Sect. 6 we estimate the helium difference between the two stellar populations of NGC 6121 and NGC 6752. A summary follows in Sect. 7.

<sup>★</sup> Based on observations at the European Southern Observatory using the Very Large Telescope on Cerro Paranal through ESO programme 089.D-0978 (P. I. G. Piotto)



**Fig. 1.** Dither pattern of the FORS2 images taken in the fields of NGC 6121 (left), NGC 6397 (middle), and NGC 6752 (right). The dotted, dashed, and dashed-dotted circles indicate the core, the half-light, and the tidal radius of the three GCs. NGC 6397 and NGC 6752 are both post core collapse clusters.

## 2. Properties of the target GCs

Multiple stellar populations have been widely studied in the three GCs analyzed in this paper. In this section we summarize the observational scenario and provide useful information to interpret our observations.

### 2.1. NGC 6121

NGC 6121 is the closest GC ( $d \sim 2.2$  kpc) and has intermediate metal abundance ( $[\text{Fe}/\text{H}] = -1.16$  Harris 1996, 2010 edition).

The RGB stars of this cluster exhibit a large spread in the abundance distribution of some light-elements such as C, N, O, Na and Al (Gratton et al. 1986; Brown et al. 1990; Drake et al. 1992; Smith & Briley 2005). There is evidence of a CN bimodality distribution and Na-O anticorrelation (e.g. Norris 1981; Ivans et al. 1999).

The distribution of sodium and oxygen is also bimodal. Sodium-rich (oxygen-poor) stars define a red sequence along the RGB in the  $U$  versus  $U - B$  CMD, while Na-poor stars populate a bluer RGB sequence (Marino et al. 2008). Further evidence of multiple sequences along the RGB of NGC 6121 are provided by Lee et al. (2009) and Monelli et al. (2013). NGC 6121 has a bimodal HB, populated both on the blue and red side of the instability strip. The HB morphology of this cluster is closely connected with multiple stellar populations, indeed blue HB stars are all Na-rich and O-poor (hence belong to the second stellar generation) while red-HB stars have the same chemical composition as first-generation ones (Marino et al. 2011).

### 2.2. NGC 6397

Located at a distance of 2.3 kpc, NGC 6397 is a very metal-poor GC ( $[\text{Fe}/\text{H}] = -2.02$ ; Harris 1996, 2010 edition).

In late 1970s, Bell et al. (1979) have already demonstrated that the RGB stars of this cluster show a spread in light-element abundance. NGC 6397 exhibits modest star-to-star variations of oxygen and sodium and a mild Na-O anti-correlation (e.g. Ramírez & Cohen 2002, Carretta et al. 2009). Similarly to NGC 6121 the distribution of sodium and oxygen is bimodal, and the groups of Na-rich (O-poor) and Na-poor (O-rich) stars populate two distinct RGBs in the Strömgren  $y$  versus  $c_y$  index diagram (Lind et al. 2011).

The MS of NGC 6397 is also bimodal, but the small color separation between the two MSs can be detected only when appropriate filters (like the F225W, F336W from *HST*/WFC3) are used. Observations of the double MSs from multi-wavelength *HST* photometry have been interpreted with two stellar populations with different light-element abundance and a modest helium variation of  $\Delta Y \sim 0.01$  (di Criscienzo et al. 2010, Milone et al. 2012a).

### 2.3. NGC 6752

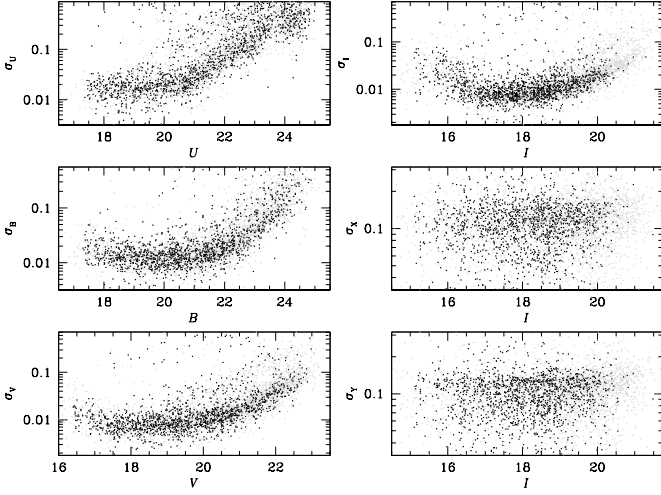
NGC 6752, is a nearby metal-poor GC ( $d = 4.0$  kpc,  $[\text{Fe}/\text{H}] = -1.54$ ; Harris 1996, 2010 edition).

Since the 1980s, spectroscopic data reported ‘anomalies’ in the light-element abundances of the RGB stars of this cluster (Norris et al. 1981, Cottrell & Da Costa 1981). More recent works confirm star-to-star light-element variations in NGC 6752 (Grundahl et al. 2002; Yong et al. 2003, 2008, 2013; Carretta et al. 2005), O-Na, Mg-Al, C-N (anti-)correlations for both unevolved (Gratton et al. 2001; Shen et al. 2010; Pancino et al. 2010) and RGB stars (Yong et al. 2005; Carretta et al. 2007, 2012) in close analogy with what was observed in most Galactic GCs (see e.g. Ramírez & Cohen 2002, Carretta et al. 2009 and references therein). In particular, there are three main groups of stars with different Na, O, N, Al, that populates three different RGBs when appropriate indices are used (like the  $c_1$  and  $c_y$  Strömgren indices or the  $c_{U,B,I}$  visual index, Yong et al. 2008, 2003, Carretta et al. 2012, Monelli et al. 2013).

As shown by Milone et al. 2013 (hereafter Mi13), the CMD of NGC 6752 is made of three distinct sequences that can be followed continuously from the MS to the SGB and from the SGB to the RGB. These sequences correspond to three stellar populations with different light-element and helium abundance.

## 3. Observations and data reduction

For this work we used  $2 \times 2$  binned images taken with the ESO/FORS2 ( $2 \times 2 \text{ k} \times 4 \text{ k}$  MIT CCDs) mounted at the VLT, using the standard resolution collimator. With this configuration, the field of view of FORS2 is reduced to  $\sim 6.8 \times 6.8$  by the MOS unit in the focal plane and the pixel scale is  $\sim 0.25''/\text{pixel}$ . The dithered images of NGC 6121, NGC 6397 and NGC 6752 were



**Fig. 2.** The photometric (left panels and top-right panel) and position residuals (middle- and bottom-right panels) from the single measurements in the single images of NGC 6121 plotted as a function of the average magnitude. Grey points show all detected stars; black points refer to proper motion selected stars. In the case of NGC 6752 and NGC 6397 the distributions are similar.

acquired using u\_HIGH, b\_HIGH, v\_HIGH and I\_Bessel broad band filters between April 14, 2012 and July 23, 2012. A detailed log of observations is reported in Table 1. Figure 1 shows the combined field of view for each cluster.

For the data reduction we used a modified version of the software described in Anderson et al. (2006). Briefly, for each image we obtained a grid of 18 spatially varying empirical point spread functions (PSFs, an array of  $3 \times 3$  PSFs for each chip of FORS2) using the most isolated, bright and not saturated stars. In this way, to each pixel of the image corresponds a PSF that is a bi-linear interpolation of the closest four PSFs of the grid. This makes it possible to measure star positions and fluxes in each individual exposure using an appropriate PSF and to obtain a catalog of stars for each frame. We registered, for each cluster and for each filter, all star positions and magnitudes of each catalog into a common frame (master-frame) using linear transformations. The final result is a list of stars (master list) for each cluster. For each filter and each star measured in NGC 6121, in Fig. 2 we plot the rms of the photometric residual and of the position as a function of the mean magnitude. In the case of NGC 6752 and NGC 6397 the distributions are similar. As required by the referee, we specify here that we used magnitude to express the luminosities of stars in this paper.

We noted that all the CMDs of the three GCs showed unusually spread out sequences (see panel (a) of Fig. 3 for an example of the  $V$  versus  $U - V$  CMD of NGC 6397). Part of this spread is due to differential reddening, but this is not the only cause. In fact, we found that, selecting stars in different regions of the master list, we obtained shifted MSs. As an example, in panel (d) of Fig. 3 we show the variation of the color  $\Delta(U - V)$  for NGC 6397. This plot shows that there is an important gradient of  $\Delta(U - V)$  along the x-axis. We selected in this plot two groups of stars: the stars with  $x > 1050$  and that with  $x < 1050$ . We plotted these two sub-samples in the  $V$  versus  $U - V$  CMDs, respectively in black crosses ( $x > 1050$ ) and red circles ( $x < 1050$ ): panel (a) of Fig. 3 shows the result. The two groups form two shifted MSs. This effect is present in all the CMD of the three GCs, even if with different extent levels.

**Table 1.** Log of observations

Filter	Exp. time	Airmass (sec z)	Seeing (arcsec)
<b>NGC 6121</b>			
u_HIGH	25 × 410 s	1.004–1.104	0′:58–0′:90
b_HIGH	25 × 200 s	1.007–1.113	0′:71–1′:20
v_HIGH	25 × 52 s	1.118–1.251	0′:70–1′:21
I_BESS	25 × 30 s	1.036–1.150	0′:56–1′:03
<b>NGC 6397</b>			
u_HIGH	25 × 410 s	1.153–1.452	0′:81–1′:09
b_HIGH	35 × 200 s	1.144–1.599	0′:73–1′:52
v_HIGH	50 × 52 s	1.142–1.272	0′:82–1′:23
I_BESS	25 × 30 s	1.251–1.355	0′:70–1′:21
<b>NGC 6752</b>			
u_HIGH	25 × 410 s	1.227–1.416	0′:67–1′:30
b_HIGH	33 × 200 s	1.227–1.850	0′:49–1′:36
v_HIGH	25 × 52 s	1.367–1.483	0′:68–0′:86
I_BESS	25 × 30 s	1.293–1.363	0′:50–0′:77

Freudling et al. (2007) showed that there is an illumination gradient in the FORS2 flats produced by the twilight sky. This gradient changes with time and with the position of the Sun relative to the pointing of the telescope and could produce a photometric zero point variation across the FORS2 detectors.

The illumination gradient in the flat fields could contribute to the observed enlargement of the CMDs.

We obtained star fluxes using local sky values, and therefore it is expected that these systematic effects are negligible. If the gradient in the flat-field images is not properly removed during the pre-reduction procedure, the pixel quantum efficiency correction will be wrong. The consequence is that the luminosity of a star measured in a given location of the CCD will be underestimated (or overestimated) with respect to the luminosity of the same star measured in another location of the CCD.

Using the measured star positions and fluxes, we performed a correction in a similar way to what described by Bellini et al. (2009a). It is a self-consistent auto-calibration of the illumination map and takes advantage of the fact that the images are well dithered.

For each cluster and for each filter, the best image (characterized by lower airmass and best seeing) is defined as reference frame. We considered the measured raw magnitude  $m_{ij}$  of each star  $i$  in each image  $j$ . Using common stars between the image  $j$  and the reference frame we computed the average magnitude shift:

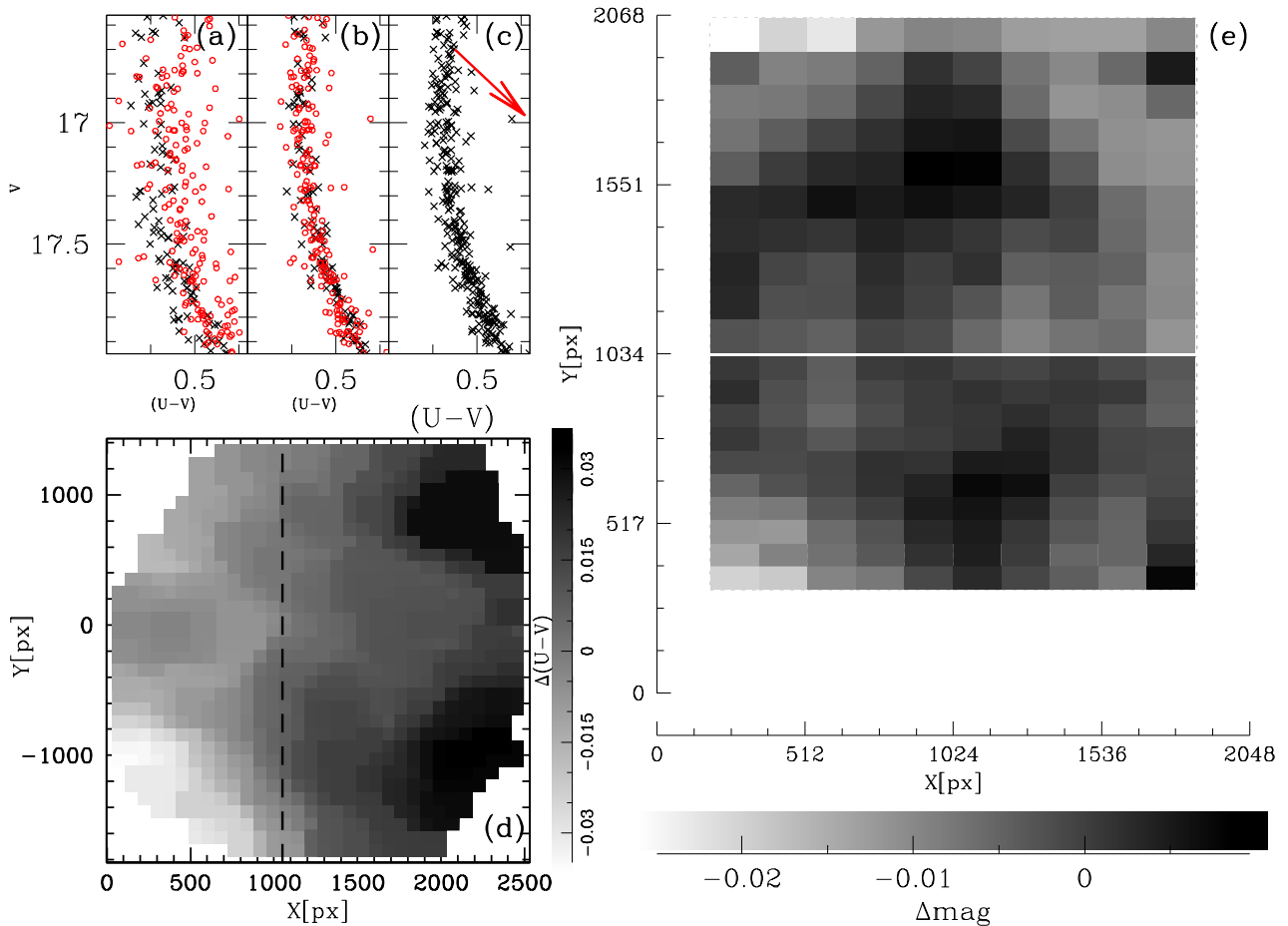
$$\Delta_j = \frac{1}{M} \sum_{i=1}^M (m_{ij} - m_{i,\text{ref}})$$

where  $M$  is the number of stars in common between the reference frame and the single image  $j$ . For each star, that is centered in a different pixel in each dithered frame, we computed its average magnitude in the reference system:

$$\bar{m} = \frac{1}{N} \sum_{j=1}^N (m_{ij} - \Delta_j)$$

where  $N$  is the number of images in which the star appears. Then we computed the residual:

$$\delta_{ij} = m_{ij} - \Delta_j - \bar{m}_j.$$



**Fig. 3.** Visualization of the effects of the photometric zero point variation. Panel (a): CMDs zoomed into the MS region of NGC 6397 before the zero-point correction; panel (b): CMD after the zero-point correction; panel (c): CMD after the differential reddening correction (in red the reddening vector, scaled by a factor 1/3); panel (d): map of the color zero point variation; the dashed line divide the two groups of stars showed in the panels (a) and (b); panel (e): final  $\Delta\text{mag}$  correction grid for the filter  $v_{\text{HIGH}}$  and the NGC 6397 data-set.

We divided each FORS2 chip in a spatial grid of  $10 \times 10$  boxes, and, for each box, we computed the average of the residuals from the stars located in that region in each single image. This provides a first spatial correction to our photometry. To obtain the best correction, we iterate until the residual average became smaller than 1 mmag. To guarantee convergence we applied, for each star, half of the correction calculated in each box. Moreover, to obtain the best correction at any location of the camera, we computed a bi-linear interpolation of the closest 4 grid points. At the edges of the detectors the correction is less efficient, because the corresponding grid-points have been moved toward the external borders of the grid to allow the bi-linear interpolation to be computed all across the CCDs. In panel (e) of Fig. 3 we show our final correction grid for the  $v_{\text{HIGH}}$  filter.

The final correction grids are different for each filter and for each set of images. In particular, the patterns are different from filter to filter, as well as the size of the zero point variations. This quantity also changes using different data-sets. The maximum amplitudes of our corrections are tabulated in Table 2.

We corrected the spread of the CMD due to differential reddening using the procedure as described by Milone et al. (2012b). Briefly, we defined a fiducial line for the MS of the cluster. Then, for each star, we considered a set of neighbors (usually 30, selected anew for each filter combination) and estimated the median offset relative to the fiducial sequence. These systematic color and magnitude offsets, measured along the red-

**Table 2.** Maximum amplitudes of photometric zero-points corrections.

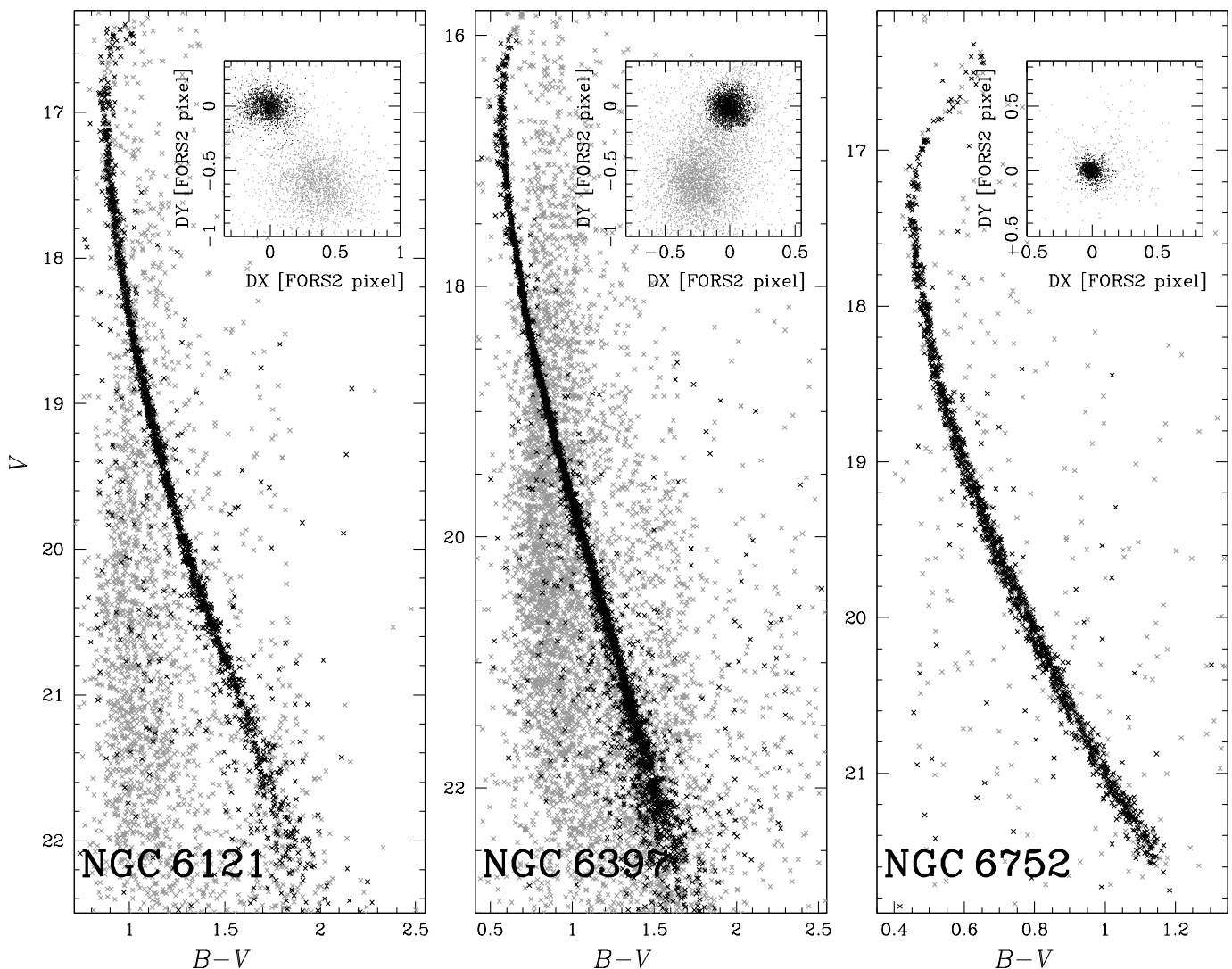
Filter	$\Delta\text{mag}$		
	NGC 6121	NGC 6397	NGC 6752
u_HIGH	0.11	0.13	0.09
b_HIGH	0.04	0.05	0.03
v_HIGH	0.12	0.04	0.06
I_BESS	0.04	0.04	0.04

dening line, represent an estimate of the local differential reddening. With this procedure we also mitigated the photometric zero-point residuals left by the illumination correction (especially close to the corners of the field of view). Panel (c) of Fig. 3 shows the CMD after all the corrections are applied.

The photometric calibration of FORS2 data for  $UBV$  Johnson and  $I_C$  Cousins bands was obtained using the photometric Secondary Standards star catalog by Stetson (2000). We matched our final catalogs to the Stetson standard ones, and derived calibration equations by means of least squares fitting of straight lines using magnitudes and colors.

### 3.1. Proper motions

Since NGC 6121 ( $l, b = 350^\circ 97', 15^\circ 97'$ ) and NGC 6397 ( $l, b = 338^\circ 17', -11^\circ 96'$ ) are projected at low Galactic latitude,



**Fig. 4.**  $V$  versus  $B - V$  CMD of stars in the field of view of NGC 6121 (left), NGC 6397 (middle), and NGC 6752 (right). The insets show the vector-point diagram of stellar displacements along the X and Y direction. Black and gray points indicate stars that, according to their proper motions, are considered cluster members and field stars, respectively (see text for details).

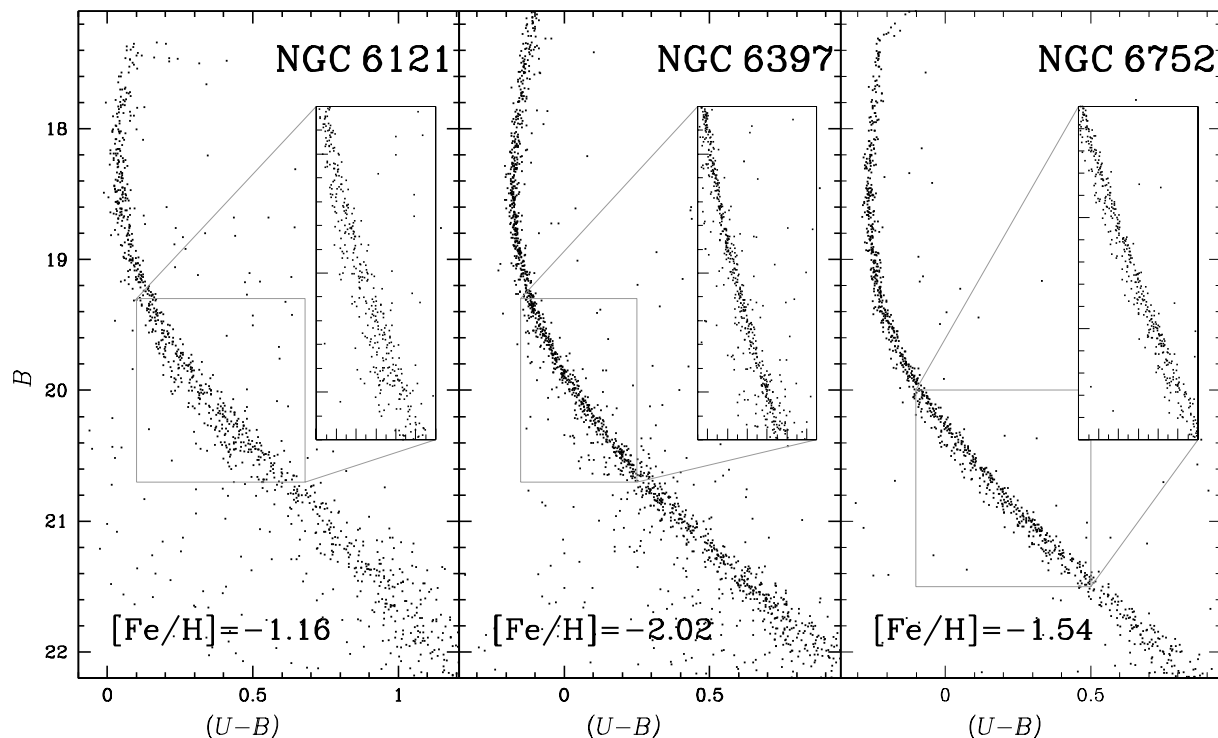
their CMDs are both dramatically contaminated by Disk and Bulge stars, contrary to NGC 6752 ( $l, b = 336^\circ 49'; -25^\circ 63'$ ) that presents low field contamination. The average proper motions of NGC 6121, NGC 6397 and NGC 6752 strongly differ from that of these field stars (e.g. Bedin et al. 2003, Milone et al. 2006). Therefore, to minimize the contamination from field stars we identified cluster members on the basis of stellar proper motions.

In order to get information on the cluster membership, we estimated the displacement between the stellar positions obtained from our FORS2 data-set and those in the ground-based data taken from the image archive maintained by Stetson (2000) and also used in Monelli et al. (2013). These observations include images from different observing runs with the Max Planck 2.2m telescope, the CTIO 4m, 1.5m and 0.9m telescopes and the Dutch 0.9m telescope on La Silla. To obtain the displacement, we used six-parameter local transformations based on a sample of likely cluster members, in close analogy to what was done by Bedin et al. (2003) and Anderson et al. (2006) to calculate stellar proper motions.

Results are shown in Fig. 4. The figure shows the  $V$  versus  $B - V$  CMDs for NGC 6121, NGC 6397 and NGC 6752. The insets show the vector-point diagrams of the stellar displacements for the same stars shown in the CMDs: the cluster-field separation is evident. Likely cluster members are plotted in black both in the CMDs and in the vector-point diagrams, in gray the rejected stars.

#### 4. The CMDs of the three GCs

Previous studies on multiple stellar populations have demonstrated that the  $U - B$  color is very efficient in detecting multiple RGBs (see Marino et al. 2008 and Milone et al. 2010 for the cases of NGC 6121 and NGC 6752), and multiple MSs (see Milone et al. 2012b, Mi13 for the cases of NGC 6397 and NGC 6752). As discussed by Sbordone et al. (2011), CNO abundance variations affect wavelengths shorter than  $\sim 400$  nm owing to the rise of molecular absorption bands in cooler atmospheres. The consequences are that the CMDs in  $UB$  filters show enlarged sequences, mainly due to variations in the N abundance, with the largest variations affecting the RGB and the lower MS.



**Fig. 5.**  $B$  versus  $(U - B)$  CMD for NGC 6121 (left), NGC 6397 (middle), and NGC 6752 (right). The inset is a zoom around the upper MS. The CMDs only show the cluster members and are corrected by zero point variations and differential reddening

Motivated by these results, we started our analysis from the  $B$  versus  $U - B$  CMDs shown in Fig. 5; the inset of each panel is a zoom in of the upper MS, between  $\sim 1.5$  and  $\sim 2.5$  magnitudes below the turn off.

A visual inspection at these CMDs reveals that the color broadening of MS stars in both NGC 6121 and NGC 6752 is larger than that of NGC 6397. A small fraction of MS stars in NGC 6121 and NGC 6752 defines an additional sequence on the blue side of the most-populous MS.

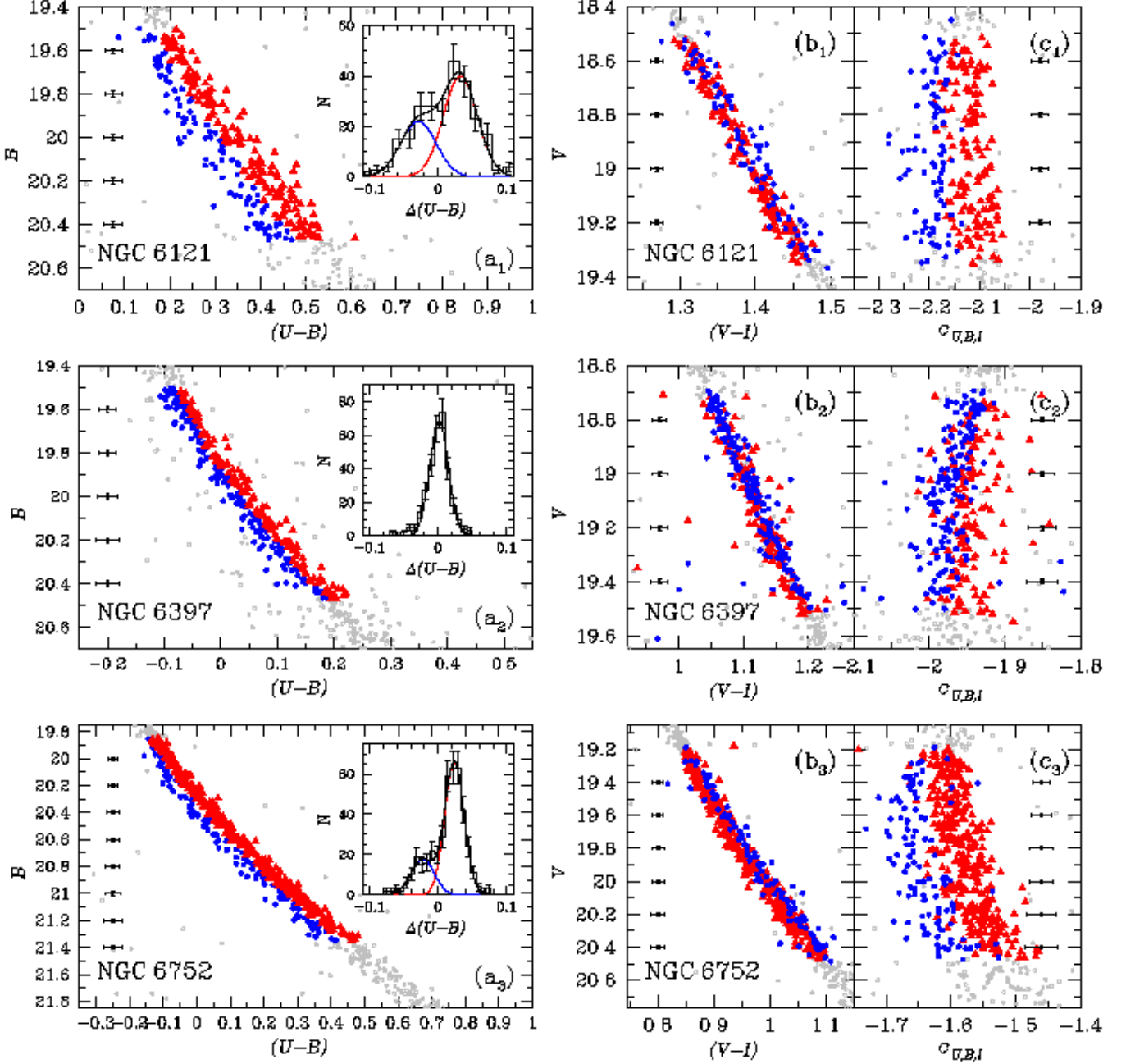
To investigate whether the widening of the MSs is due to the presence of multiple populations we identified in the  $B$  versus  $U - B$  CMD of each cluster two groups of red-MS (rMS) and blue-MS (bMS) stars, as shown in panels (a) of Fig. 6. We colored the two MSs in red and blue respectively, and these colors are used consistently hereafter. In the case of NGC 6121 and NGC 6752, where there is some hint of a split MS, we identified by eye the fiducial that divide the rMS and bMS. In the case of NGC 6397 we have considered as rMS (or bMS), the stars that are redder (or bluer) than the MS fiducial line. Each inset shows the color distribution of  $\Delta(U - B)$  for the two MSs, where  $\Delta(U - B)$  is obtained by subtracting the color of the fiducial that divide the two MSs to the color of the rMS and bMS stars. In the cases of NGC 6121 and NGC 6752 the color distributions show a double peak that could be due to the presence of two populations; we fitted them with a sum of Gaussians (in red and blue respectively for the rMS and bMS). We applied a moving box procedure to further verify that the distribution of  $\Delta(U - B)$  in the case of NGC 6121 is bimodal. We changed the binsize, ranging from 0.005 to 0.02 (approximately the error in color) with steps of 0.001. Furthermore, from our dataset we determined a kernel-density distribution by assuming a Gaussian kernel with  $\sigma = 0.02$  mag. In all cases, we consistently found that the distribution can only be reproduced by two Gaussians.

A multiple sequence in NGC 6752 had already been identified by Mi13 using *HST* data. Very recently, we had the first F275W, F336W, F438W WFC3 images of NGC 6121 from the *HST* GO-13297 UV Large Legacy Program (P.I. Piotto). Even a preliminary reduction of the data shows a clear separation of the MS into two branches in the F438W vs F336W-F438W CMD, fully confirming what we anticipate here in the equivalent, groundbased  $U$  vs  $U - B$  diagram of Fig. 6.

In the case of NGC 6397, it is possible to fit the distribution with a single Gaussian.

As an additional check for the presence of multiple populations, we investigated whether the widening of the MSs of all the GCs is intrinsic or if it is entirely due to photometric errors. We have compared two CMDs,  $B$  versus  $U - B$  with  $V$  versus  $V - I$ , obtained using independent datasets. We considered the rMS and bMS defined previously: if the color spread is entirely due to photometric errors, a star which is red (or blue) in the  $B$  versus  $U - B$  CMD will have the same chance of being either red or blue in the  $V$  vs  $V - I$ . By contrast, the fact that the two sequences identified in the first CMD have systematically different colors in the second one, would be a proof that the color broadening of the MS is intrinsic. In panels (b) of Fig. 6 we plotted the rMS and bMS in  $V$  versus  $V - I$  CMDs. The fact that the rMS stars of both NGC 6121 and NGC 6752 have, on average, different  $V - I$  than bMS stars demonstrates that the color broadening of their MS in the  $U$  versus  $U - B$  CMDs is intrinsic. This is the first evidence that the MS of NGC 6121 is not consistent with a simple stellar population. In the case of NGC 6397 rMS and bMS stars share almost the same  $V - I$  thus suggesting that most of the colors broadening is due to photometric errors.

As last test, we plotted the two MSs in the  $V$  versus  $c_{U,B,I}$  CMD. The  $c_{U,B,I}$  index, which is defined as the color difference  $(U - B) - (B - I)$ , is a very efficient tool to identify mul-



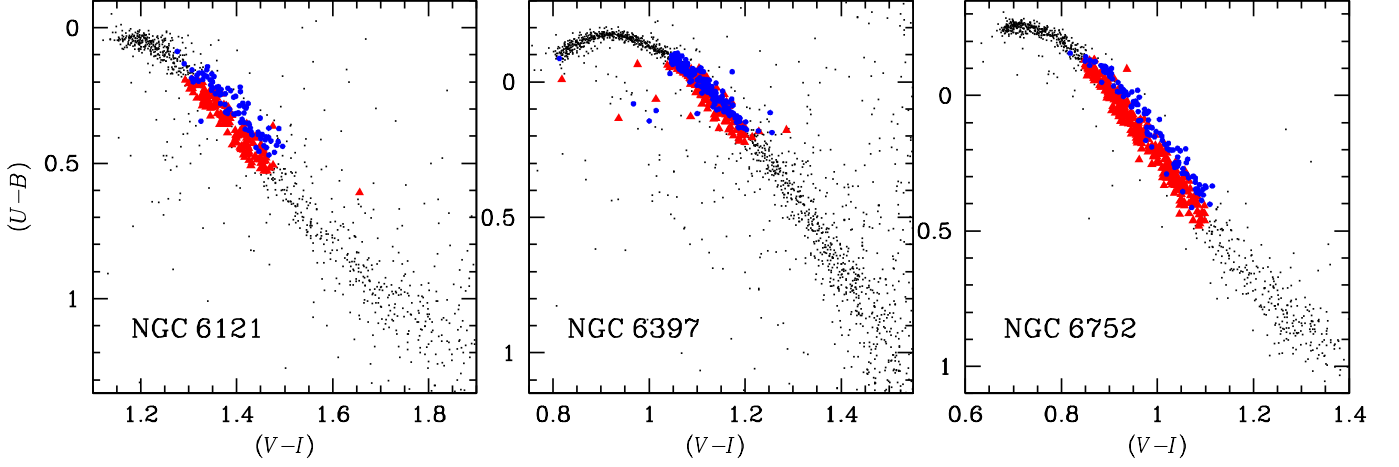
**Fig. 6.** Comparison between the  $B$  vs.  $U - B$  (panels a), the  $V$  vs.  $V - I$  (panels b) and  $V$  vs.  $c_{U,B,I}$  (panels c) CMDs of NGC 6121 (up), NGC 6397 (middle) and NGC 6752 (down). Red triangles and blue points represent the groups of rMS and bMS stars defined in panels (a). The insets of panels (a) show the  $\Delta(U - B)$  distributions, fitted with a bi-Gaussian in the case of NGC 6121 and NGC 6752 and with a Gaussian in the case of NGC 6397. The horizontal bars show the mean error in color.

multiple sequences in GCs. Indeed it maximizes the color separation between the stellar populations that is due to both helium and light-element variations (Monelli et al. 2013). Panels (c) of Fig. 6 confirm the previous results: rMS and bMS of NGC 6121 and NGC 6752 are well defined in the  $V$  versus  $c_{U,B,I}$  CMDs, but this is less evident for NGC 6397.

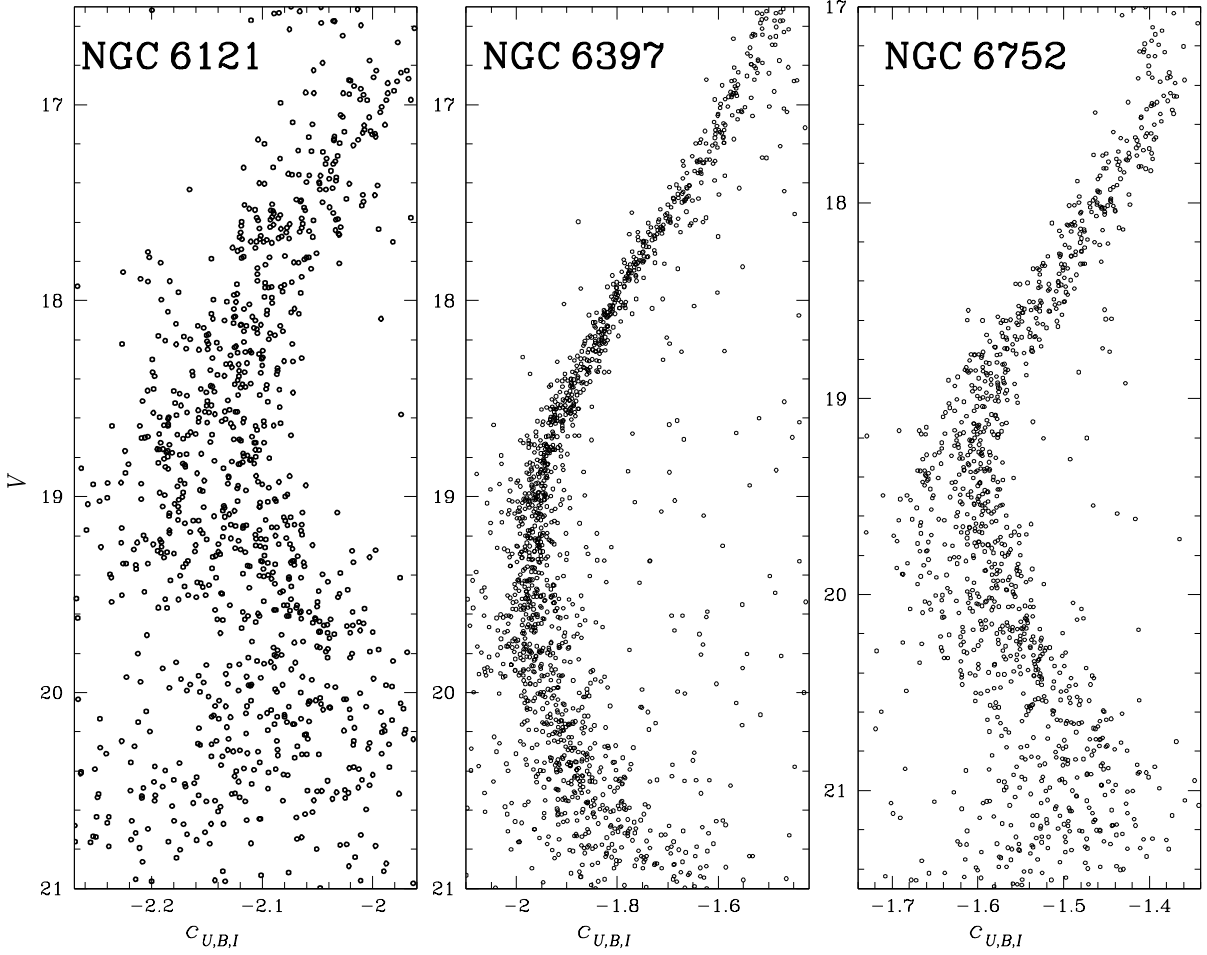
As a last prof, we plotted in Fig. 7 the  $(U - B)$  versus  $(V - I)$  diagrams for each cluster: in red and in blue are plotted the rMS and bMS defined previously. The figure shows that for both NGC 6121 and NGC 6752 the two MSs are well defined, while for NGC 6397 the rMS and bMS stars are mixed

Figure 8 shows the  $V$  versus  $c_{U,B,I}$  diagram for the three GCs studied in this paper. In their analysis of multiple stellar populations in 22 GCs, Monelli et al. (2013) found that all the analyzed clusters show a multimodal or spread RGB in the  $V$  versus  $c_{U,B,I}$  diagram, and the  $c_{U,B,I}$  value of each star depends on its light-element abundance. The  $c_{U,B,I}$ -index width of the RGB ( $W_{\text{RGB}}$ ) correlates with the cluster metallicity, with the more metal rich GCs having also the largest values of  $W_{\text{RGB}}$ . In order to compare the MSs of the three GCs studied in this paper, we introduce a quantity,  $W_{\text{MS}}$ , which is akin of  $W_{\text{RGB}}$ , but is indicative of the  $c_{U,B,I}$ -index broadening of the MS. The procedure





**Fig. 7.** Color-color diagrams for NGC 6121 (*left panel*), NGC 6397 (*central panel*) and NGC 6752 (*right panel*). In red (triangles) and blue dots the rMS and bMS as defined in Fig. 6



**Fig. 8.**  $V, C_{U,B,I}$  diagrams for NGC 6121 (*left*), NGC 6397 (*middle*) and NGC 6752 (*right*).

to determine  $W_{MS}$  is illustrated in Fig. 9 for NGC 6121 and is the same for the other clusters. We have considered the magnitude of the TOs as magnitude of reference:  $V_{MSTO} \sim 16.6$  in the case of NGC 6397,  $V_{MSTO} \sim 17.4$  for NGC 6752, and  $V_{MSTO} \sim 16.75$  for NGC 6121. Panel (a) of Fig. 9 shows the  $V$  versus  $C_{U,B,I}$  diagram for NGC 6121 in a range of magnitudes from  $V_{MSTO} - 0.5$  to  $V_{MSTO} + 5$ . In this range of magnitudes,

we obtained the fiducial line for the MSs computing the  $3.5\sigma$ -clipped median of the color in interval of 0.35 mag and interpolated these points with a spline. In our analysis we used only MS stars with  $2 < V - V_{MSTO} < 2.5$  where the MS split is visible for both NGC 6121 and NGC 6752. This magnitude interval is delimited by the two dashed lines of Fig. 9a. The thick line is the fiducial in the considered magnitude interval. The



verticalized  $V$  versus  $\Delta c_{U,B,I}$  diagrams is plotted in panel (b) of Fig. 9, while panel (c) shows the histogram distribution of  $\Delta c_{U,B,I}$ . The MS width,  $W_{\text{MS}}$ , is defined as the  $\Delta c_{U,B,I}$  extension of the histogram and is obtained by rejecting the 5% of the reddest and the bluest stars on the extreme sides. To account for photometric error, we have subtracted from the observed  $W_{\text{MS, OBS}}$  the average error in  $c_{U,B,I}$  in the same magnitude interval, i.e.

$$W_{\text{MS}} = \sqrt{W_{\text{MS, OBS}}^2 - \sigma_{c_{U,B,I}}^2}.$$

We found that the most metal-rich GC, NGC 6121, exhibits the largest  $c_{U,B,I}$  index width for MS stars ( $W_{\text{MS}} = 0.169 \pm 0.014$ ). The spread in  $c_{U,B,I}$  is smaller in the case of NGC 6752 ( $W_{\text{MS}} = 0.115 \pm 0.006$ ) and drops down to  $W_{\text{MS}} = 0.093 \pm 0.014$  in the most metal-poor GC NGC 6397. To estimate the statistical uncertainty in measuring  $W_{\text{MS}}$ , we used the bootstrap resampling of the data to generate 10000 samples drawn from the original data sets. We computed the standard deviation from the mean of the simulated  $W_{\text{MS}}$  and adopted this as uncertainty of the observed  $W_{\text{MS}}$ .

These findings make it tempting to speculate that the  $c_{U,B,I}$  index width of the MS could be correlated with the cluster metallicity, in close analogy with what observed for RGB stars. An analysis of a large sample of GCs is mandatory to infer any conclusion on the relation between  $W_{\text{MS}}$  and  $[\text{Fe}/\text{H}]$ .

Mi13 have identified three stellar populations in NGC 6752 that they have named ‘a’, ‘b’, and ‘c’. Population ‘a’ has a chemical composition similar to field halo stars of the same metallicity, population ‘c’ is enhanced in sodium and nitrogen, depleted in carbon and oxygen and enhanced in helium ( $\Delta Y \sim 0.03$ ), while population ‘b’ has an intermediate chemical composition between ‘a’ and ‘c’ and is slightly helium enhanced ( $\Delta Y \sim 0.01$ ). However, the MSs of populations ‘b’ and ‘c’ are nearly coincident in the  $m_{\text{F336W}}$  versus  $m_{\text{F336W}} - m_{\text{F390W}}$  CMD, while population ‘a’ stars have bluer  $m_{\text{F336W}} - m_{\text{F390W}}$  colors (Mi13, see their Fig. 8). The three MSs exhibit a similar behavior also in the  $m_{\text{F336W}} - m_{\text{F410M}}$  and  $m_{\text{F336W}} - m_{\text{F467M}}$  colors. Since these colors are similar to  $U - B$ , the less populous MS identified in this paper should correspond to the population ‘a’ identified by Mi13, while the rMS hosts both population ‘b’ and population ‘c’ stars.

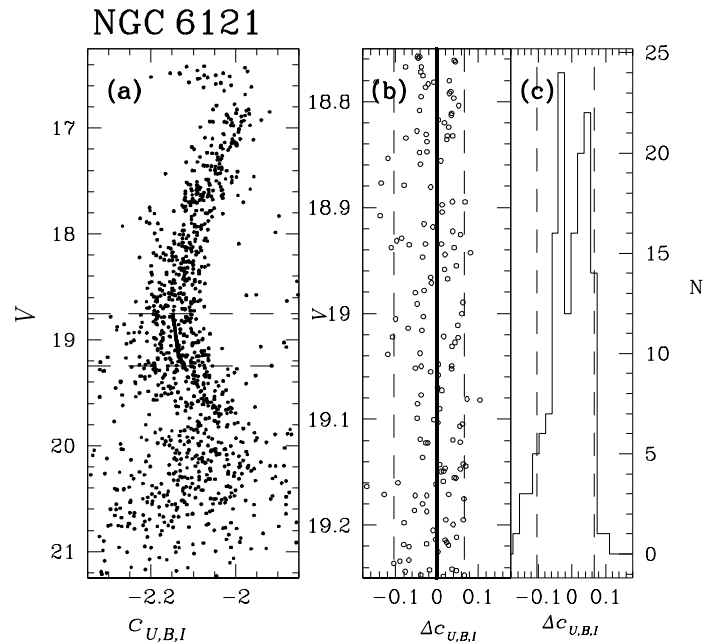
#### 4.1. The fraction of rMS and bMS in NGC 6121 and NGC 6752

In order to measure the fraction of stars in each MS we followed the procedure illustrated in Fig. 10 for NGC 6752, which we already used in several previous papers (e.g. Piotto et al. 2007, Mi13).

Panel (a) shows the  $V$  versus  $c_{U,B,I}$  CMD of the MS stars in the magnitude interval  $19.25 < V < 20.55$ , where the MS split is most evident. We verticalized the selected MS by subtracting the color of the stars to the color of the fiducial line of the rMS, obtaining  $\Delta c_{U,B,I}$ . The fiducial line is obtained by hand selecting the stars of the rMS, dividing them in bins of magnitude, computing the median colors of the stars within each bin and interpolating these median points with a spline. The verticalized  $V$  versus  $\Delta c_{U,B,I}$  diagram is plotted in panel (b).

The  $\Delta c_{U,B,I}$  color distribution of the stars for three magnitude intervals is shown in panels (c). Each histogram clearly shows two peaks and has been simultaneously fitted with a double Gaussian, whose single components are shown in blue and in red for the bMS and the rMS, respectively.

For each magnitude interval, from the area under the Gaussians we infer the fraction of bMS and rMS stars. The errors



**Fig. 9.** Procedure to estimate the MS width for NGC 6121. Panel (a) show the  $V$  versus  $c_{U,B,I}$  CMD of NGC 6121. The thick line is the MS fiducial line (see text for details). Panel (b) shows the verticalized MS between the two dashed lines of panel (a). Panel (c) is the distribution of the color for the stars of panel (b).

( $\sigma$ ) associated to the fraction of stars are estimated as  $\sigma = \sqrt{\sigma_I^2 + \sigma_{\text{II}}^2}$ , where  $\sigma_I$  is derived from binomial statistics and  $\sigma_{\text{II}}$  is the uncertainty introduced by the histogram binning and is derived as in Libralato et al. (2014). Briefly, we have derived  $N$  times the population ratio as described above, but by varying the binning and starting/ending point in the histogram. We assumed as  $\sigma_{\text{II}}$  the rms scatter of these  $N$  determinations.

We computed the weighted mean of the bMS and rMS fractions of the three magnitude intervals, using as weight  $w = 1/\sigma^2$ . In the case of  $V$  versus  $c_{U,B,I}$ , we obtained that the rMS and bMS contain respectively  $75\% \pm 3\%$  and  $25\% \pm 5\%$  of MS stars. In panels (d), (e) and (f) of Fig. 10 we applied the same procedure in the  $B$  versus  $(U - B)$  using the stars with  $20.10 < B < 21.45$ . We obtained that the blue MS contains  $27\% \pm 5\%$  of the total number of MS stars, and the red MS is made of the remaining  $73\% \pm 3\%$  stars. We also calculated the weighted mean of the results of the two CMDs of NGC 6752, obtaining that in the rMS there are the  $74\% \pm 2\%$  of stars, and in the bMS the remaining  $26\% \pm 4\%$ .

We have already demonstrated that the  $\Delta(U - B)$  distribution, in the  $B$  versus  $U - B$  CMD of NGC 6121, shows a double peak, proving the presence of multiple populations (see panel a<sub>1</sub> of Fig. 6). We performed a detailed analysis of the MS of NGC 6121, applying the same procedure described for NGC 6752. The procedure and the results are shown in Fig. 11. We find from the analysis of the  $B$  versus  $U - B$  CMD that the bMS contains  $31\% \pm 8\%$  of MS stars, and the rMS includes the remaining  $69\% \pm 7\%$ . In the case of the  $V$  versus  $c_{U,B,I}$  diagram we infer that rMS and bMS contain  $61\% \pm 4\%$  and  $39\% \pm 5\%$  of the total number of MS stars, respectively. We computed the fraction of rMS and bMS for NGC 6121 using different histogram binsizes and changing starting/ending points. We used binsizes with values between 0.005 and 0.025 (larger than color error), starting points between -0.5 and -0.15 and ending points

between 0.15 and 0.5. In all cases, the resulting fraction of stars are in agreement with the values we quote above within the errors. The results from the two CMDs imply that in the rMS and bMS there are, respectively,  $63\% \pm 3\%$  and  $37\% \pm 4\%$  of MS stars.

## 5. The radial distribution of stellar populations in NGC 6752 and NGC 6121

The analysis of the radial distribution of rMS and bMS stars in NGC 6121 and NGC 6752 is an important ingredient to shed light on the formation and the evolution of multiple stellar populations in these GCs. Indeed, theoretical models predict that, when the GC forms, second-generation stars should be more centrally concentrated than first-generation ones, and many GCs could still keep memory of the primordial radial distribution of their stellar populations (e.g. D’Ercole et al. 2008, Bekki 2011, Vesperini et al. 2013).

The radial distribution of stellar populations in NGC 6752 is still controversial. Kravtsov et al. (2011) determined wide-field multi-band photometry of NGC 6752 and studied the distribution of its stellar populations across the field of view. They have concluded that there is a strong difference in the radial distribution between the populations of RGB stars that are bluer (bRGB) and redder (rRGB) in  $(U - B)$  color, and obtained similar findings from the study of the SGB. Specifically, at a radial distance close to the half-mass radius ( $r_h = 1.91$ ; Harris 1996, 2010 edition) the fraction of rRGB stars abruptly decreases. These results are in disagreement with the conclusions by Mi13 who showed that the three stellar populations identified in their paper share almost the same radial distribution. Kravtsov and collaborators analyzed stars with a radial distance from the center of NGC 6752 out to  $\sim 9.5$ , while the study by Mi13 is limited to the innermost  $\sim 6$  arcmin. In this paper we extend the analysis to larger radii<sup>1</sup>.

As already mentioned in Sect. 4, we suggest that the bMS of NGC 6752 corresponds to the population ‘a’ identified by Mi13, while the most populous rMS hosts both population ‘b’ and population ‘c’ stars of Mi13. For this reason, in this section, we rename the bMS in MSa and the rMS in MSbc.

In order to investigate the radial distribution of stellar populations within the field of view analyzed in this paper, we divided the catalog of NGC 6752 stars into two groups at different radial distance from the cluster center, each containing almost the same total number of stars.

The inner sample of stars (inner field) lies between 5:89 and 10:62 from the cluster center. The outer group of stars (outer field) is between 10:62 and 17:89 from the center. We estimated the fraction of stars in each group by following the same procedure described in Sect. 4.1.

The results are illustrated in Fig. 12. In the left panels we show the verticalized  $V$  versus  $\Delta_{CUB,I}$  and the  $B$  versus  $\Delta(U - B)$  diagrams for stars in the inner field. In this region the MSa contains  $27\% \pm 4\%$  and the MSbc hosts the remaining  $73\% \pm 3\%$  of the total number of MS stars. In the outer field (right panels of Fig. 12) the MSa and the MSbc are made of the  $27\% \pm 5\%$  and  $73\% \pm 3\%$  of MS stars, respectively. We conclude that there is no evidence for a gradient within the field of view studied in this paper.

<sup>1</sup> We assume that stars in the fields of NGC6752 and NGC6121 are representative of stellar populations at the studied radial distance; we are not able to investigate any dependency on the angular position using the dataset presented in this work.

**Table 3.** Fraction of POPa and POPbc Stars for NGC 6752

$R_{\min}$	$R_{\max}$	$R_{\text{ave}}$	$f_{\text{POP}a}$	$f_{\text{POP}bc}$	Seq.
0.00	1.70	0.95	$0.25 \pm 0.02$	$0.75 \pm 0.05$	MS
0.00	1.70	0.87	$0.28 \pm 0.03$	$0.72 \pm 0.04$	RGB
1.70	6.13	3.26	$0.27 \pm 0.04$	$0.73 \pm 0.06$	RGB
5.89	17.89	10.88	$0.26 \pm 0.04$	$0.74 \pm 0.02$	MS
0.00	0.53	0.31	$0.24 \pm 0.02$	$0.76 \pm 0.07$	MS
0.53	0.83	0.68	$0.23 \pm 0.02$	$0.75 \pm 0.05$	MS
0.83	1.12	0.97	$0.28 \pm 0.02$	$0.72 \pm 0.07$	MS
1.12	2.33	1.44	$0.28 \pm 0.03$	$0.72 \pm 0.05$	MS
1.70	3.11	2.35	$0.26 \pm 0.05$	$0.74 \pm 0.07$	RGB
3.11	6.13	4.15	$0.30 \pm 0.05$	$0.70 \pm 0.07$	RGB
5.89	10.62	8.63	$0.27 \pm 0.04$	$0.73 \pm 0.03$	MS
10.62	17.89	13.12	$0.27 \pm 0.05$	$0.73 \pm 0.03$	MS

To further investigate the radial distribution of stellar populations in NGC 6752 we compare the results obtained in this paper for stars with distance from the cluster center larger than  $\sim 6$  arcmin and the fraction of stars that have been estimated by Mi13 in the internal regions by using the same method.

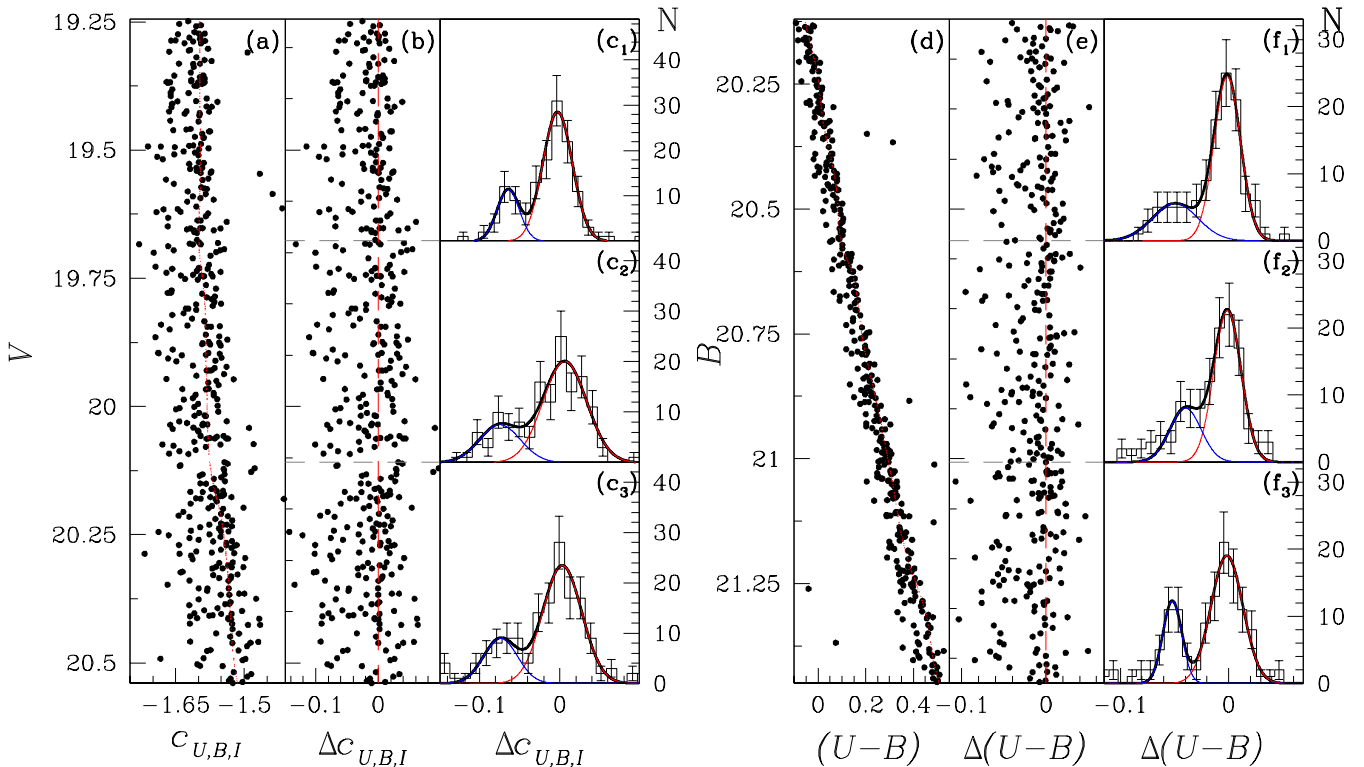
Since the MSbc contains both populations ‘b’ and population ‘c’ stars, we have added together the fractions of population ‘b’ ( $f_{\text{POP}b}$ ) and population ‘c’ stars ( $f_{\text{POP}c}$ ) listed by Milone et al. (2013, see their Table 4) and calculated the fraction of stars in these two populations:  $f_{\text{POP}bc} = f_{\text{POP}b} + f_{\text{POP}c}$ . As aforementioned in Sect. 4, we further compare the fractions of population ‘a’ stars by Mi13, with the fractions of MSa stars derived in this paper. The values of  $f_{\text{POP}a}$  and  $f_{\text{POP}bc}$  are listed in Tab. 3.

Results are shown in Fig 13, where the top panels show the distribution of the fraction of population ‘a’ (in blue) and the fraction of population ‘b’+‘c’ (in red) as a function of the radial distance from the cluster center, while the bottom panels show the radial trend of the ratio between the fraction of population ‘a’ and the fraction of population ‘b’+‘c’. In the left panels we show both the above described distributions considering single radial intervals for each set of data, while in the right panels we divided each radial interval in different bins. Our findings suggest that there is no evidence for a radial gradient among population ‘a’ and population ‘b’+‘c’ of NGC 6752.

In order to investigate the radial distribution of stellar populations in NGC 6121, we divided the field of view analyzed in this paper into two regions, with radial distance from the cluster center  $5:12 < R < 9:63$  (inner field) and  $9:63 < R < 17:81$  (outer field). Each region contains almost the same number of stars. We determined the fraction of rMS and bMS stars by following the same recipe described in detail for NGC 6752. The results are shown in Fig. 14. We found that in the inner field the fraction of bMS is  $40\% \pm 13\%$  and the fraction of rMS is  $60\% \pm 13\%$ . For the outer field we obtain that the bMS and the rMS contains respectively the  $36\% \pm 6\%$  and the  $64\% \pm 4\%$  of the total number of the considered MS. Also for NGC 6121 we found no evidence of population gradients.

## 6. The helium content of stellar populations in NGC 6121 and NGC 6752.

The ultraviolet pass-band is very efficient to separate multiple sequences due to its sensitivity to difference in C, N, O abundance (Marino et al. 2008, Sbordone et al. 2011). In contrast,  $B - I$  and  $V - I$  colors are marginally affected by light-element variations, but are very sensitive to the helium abundance of the stellar populations (e.g. D’Antona et al. 2002, Piotto et al. 2007,



**Fig. 10.** Procedure to estimate the fraction of rMS and bMS stars in NGC 6752 by using the  $V$  versus  $c_{U,B,I}$  diagram (panels (a), (b) and (c)), and the  $B$  versus  $U - B$  CMD (panels (d), (e) and (f)). Panels (a) and (d) reproduce the same diagrams as Figs. 8 and 5. The red line is the rMS fiducial line. Panels (b) and (e) show the verticalized MS. The histogram distribution of  $\Delta(\text{color})$  for the stars of the panel (b) and (e) is plotted in panels (c) and (f) for three intervals of magnitude. The tick black lines, superimposed to each histogram, are the best-fitting biGaussian functions, whose components are colored red and blue. In the case of  $V$  versus  $c_{U,B,I}$  CMD, we obtained that rMS and bMS contain respectively  $77 \pm 4\%$  and  $23 \pm 8\%$  of MS stars in panel (c1),  $74 \pm 5\%$  and  $26 \pm 8\%$  of MS stars in panel (c2) and,  $75 \pm 5\%$  and  $25 \pm 8\%$  of the MS stars. In the case of  $B$  versus  $(U - B)$  CMD we obtained that rMS a bMS contains respectively  $72 \pm 5\%$  and  $28 \pm 8\%$  of MS stars in panel (f1),  $74 \pm 6\%$  and  $26 \pm 9\%$  of MS stars in panel (f2),  $73 \pm 5\%$  and  $27 \pm 8\%$  of MS stars in panel (f3).

Sbordone et al. 2011, King et al. 2012, Cassisi et al. 2013), thus providing us with an efficient tool to infer the helium content.

### 6.1. NGC 6121

The procedure to estimate the average helium difference between bMS and rMS stars for NGC 6121 is illustrated in Fig. 15 and is already used in several papers by our group (Mi13, Milone et al. 2012a,c). Since we have already extracted the stellar populations in NGC 6121 by using the  $B$  versus  $U - B$  CMD of Fig. 11, we can now follow them in any other CMD. By combining photometry in four filters, we can construct three CMDs with  $I$  versus  $(X - I)$ , where  $X = U, B, V$ . The fiducial lines of bMS and rMS in these CMDs are plotted in the upper panels of Fig. 15. rMS is redder than bMS in  $U - I$  color, whereas it is bluer in  $B - I$  and  $V - I$  colors.

We measured the  $X - I$  color distance between the two MSs at a reference magnitude ( $I_{\text{CUT}}$ ), and repeated this procedure for  $I_{\text{CUT}} = 17.3, 17.5, 17.7, 17.9$ , and  $18.1$  (corresponding to the magnitude interval where the two MS separations is maximal, cf Fig. 6). The color difference  $\Delta(X - I)$  is plotted in the lower panel of Fig. 15 as a function of the central wavelength of the  $X$  filter (gray dots), for the case of  $I_{\text{CUT}} = 17.7$ .

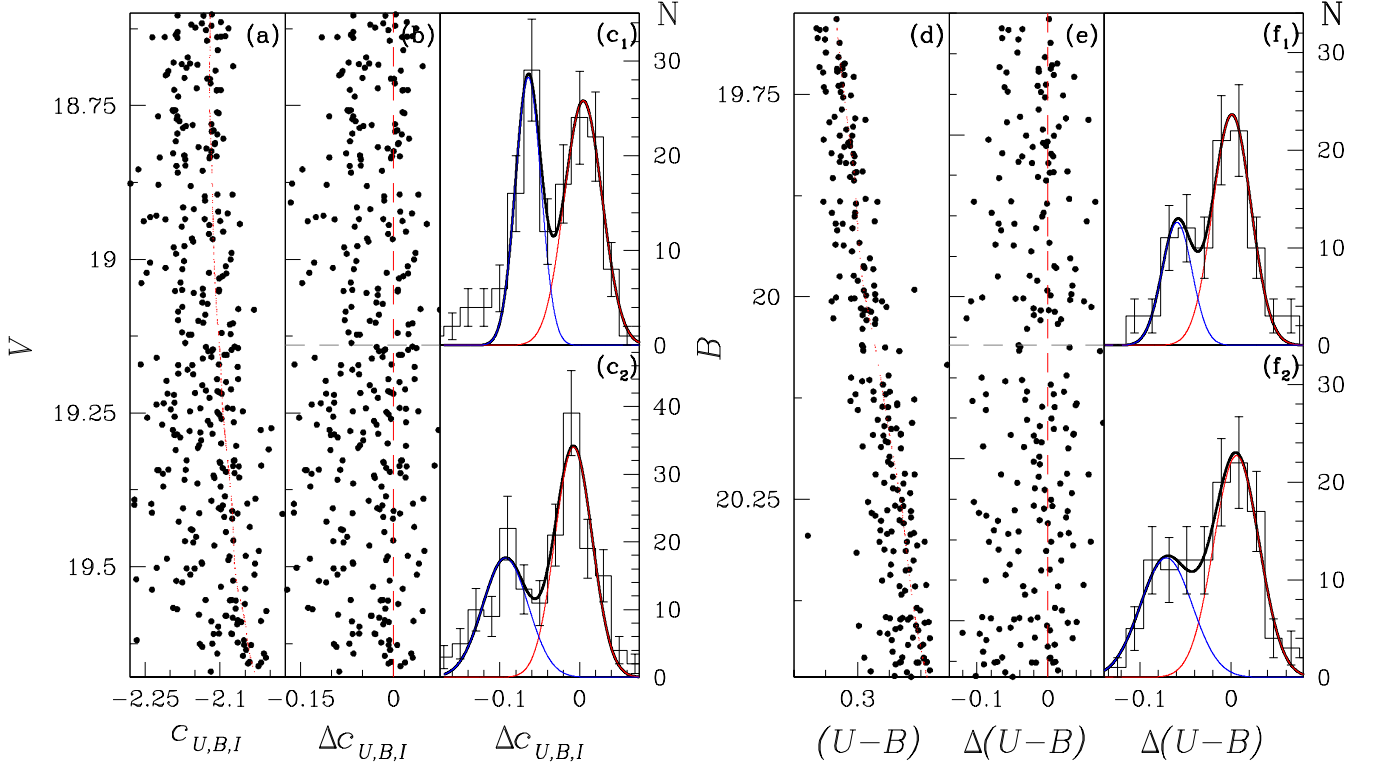
We estimated effective temperatures ( $T_{\text{eff}}$ ) and gravities ( $\log g$ ) at different  $I = I_{\text{CUT}}$  for the two MS stars and for the different helium contents by using BaSTI isochrones (Pietrinferni et al. 2004, 2009).

We assumed a primordial helium abundance for the bMS,  $Y = 0.248$ , and used for the rMS different helium content, with  $Y$  varying from 0.248 to 0.400 in steps of  $\Delta Y = 0.001$ . To account for the appropriate chemical composition of the two stellar populations of NGC 6121 we assumed for the bMS and the rMS the abundances of C, N, O, Mg, Al, and Na as measured for first and second-generation RGB stars listed by Marino et al. (2008, see their Table 6).

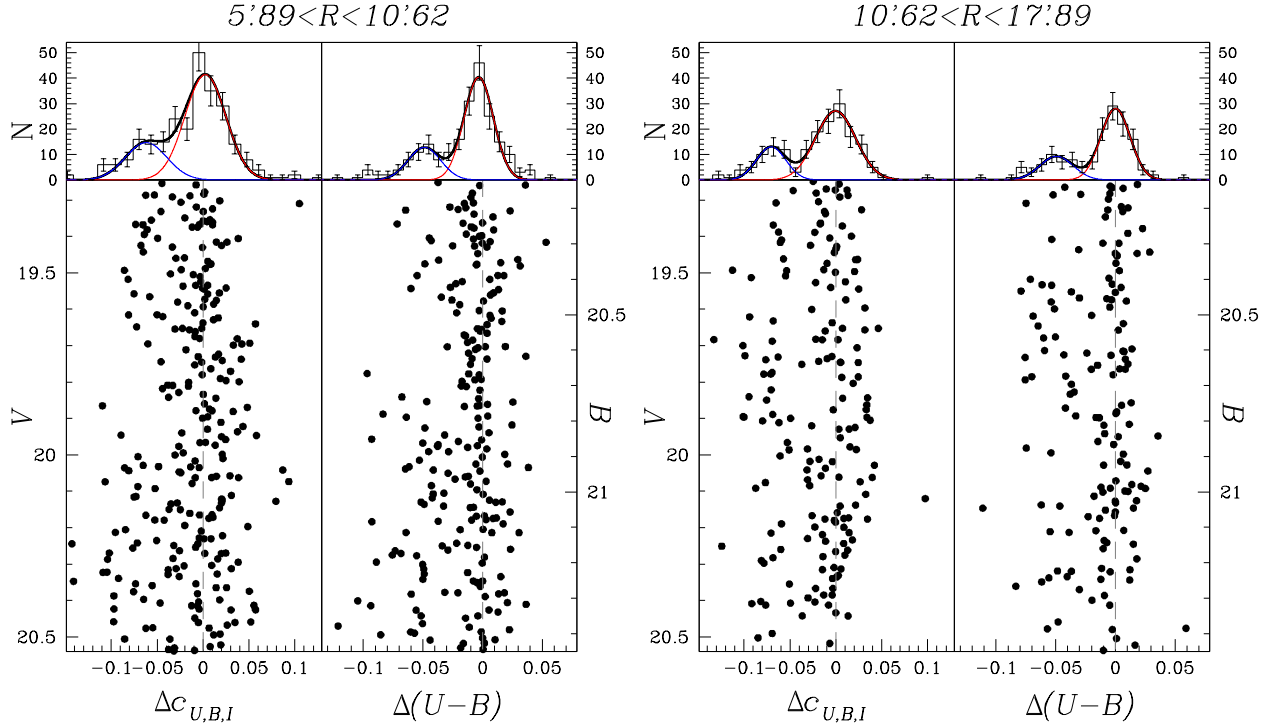
We used the ATLAS12 program and the SYNTHE code (Kurucz 2005, Castelli 2005, Sbordone et al. 2007) to generate synthetic spectra for the adopted chemical compositions, from  $\sim 2,500 \text{ \AA}$  to  $\sim 10,000 \text{ \AA}$ . Synthetic spectra have been integrated over the transmission curves of the  $U, B, V, I$  filters, and, we calculated the color difference  $X - I$  for each value of helium of our grid.

The best-fitting model is determined by means of chi-square minimization. Since the  $U$  magnitude is strongly affected by the abundance of light elements we used  $B - I$  and  $V - I$  colors only to estimate  $Y$ . The helium difference corresponding to the best-fit models are listed in Table 4 for each value of  $I_{\text{CUT}}$ .

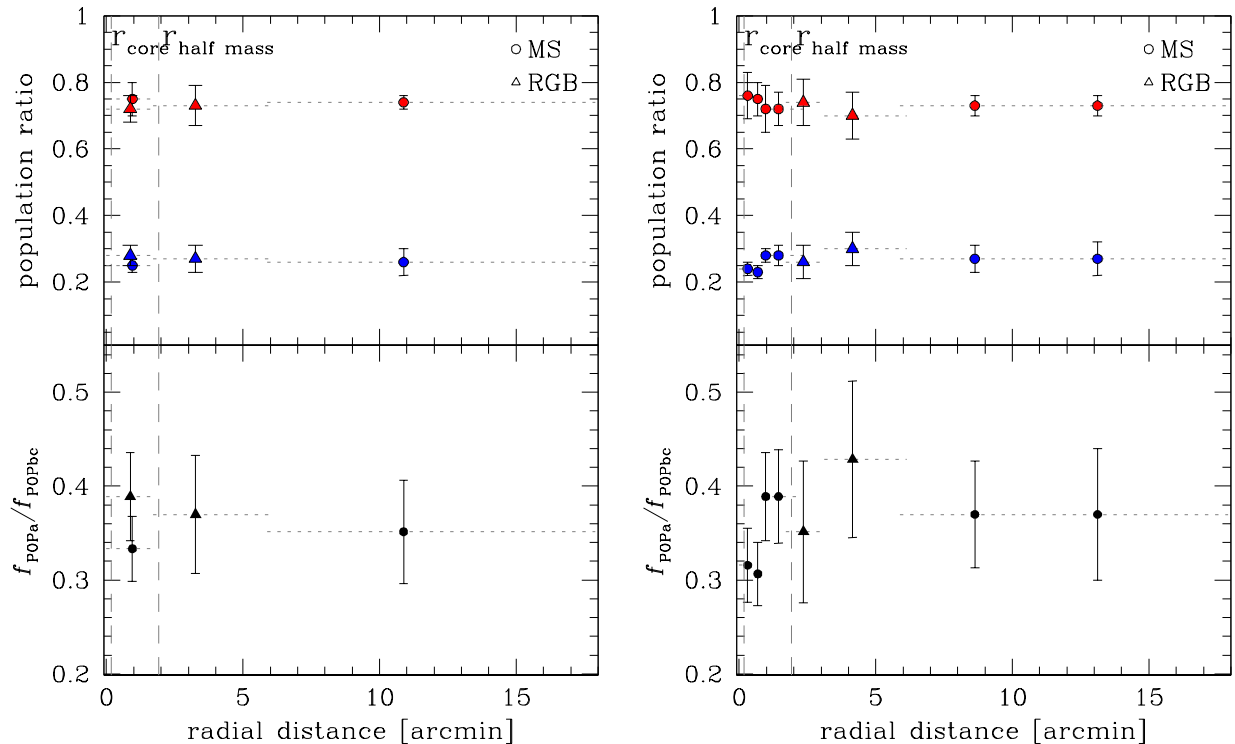
We derived that the rMS is slightly helium enhanced with respect to the bMS (which has  $Y = 0.248$ ), with an average helium abundance of  $Y = 0.268 \pm 0.008$ . This is the internal error estimated as the rms scatter of the  $N = 5$  independent measurements divided by the square root of  $N - 1$ . Results are shown in Fig. 15 for the case of  $I_{\text{CUT}} = 17.7$ , where we represented the synthetic colors corresponding to the best-fitting model as red asterisks.



**Fig. 11.** As in Fig. 10, but for NGC 6121. In the case of  $V$  versus  $c_{U,B,I}$  CMD, we obtained that rMS and bMS contain respectively  $60 \pm 7\%$  and  $40 \pm 8\%$  of MS stars in panel (c1),  $61 \pm 6\%$  and  $39 \pm 7\%$  of MS stars in panel (c2). In the case of  $B$  versus  $(U-B)$  CMD we obtained that rMS a bMS contains respectively  $67 \pm 7\%$  and  $33 \pm 10\%$  of MS stars in panel (f1),  $75 \pm 13\%$  and  $25 \pm 14\%$  of MS stars in panel (f2).



**Fig. 12.** Color distribution analysis for the MSs stars of NGC 6752 in two different radial bin, containing almost the same number (855 and 854) of stars. In the inner field (left panels) we obtained that MSa (blue) and MSbc (red) contain respectively  $28 \pm 6\%$  and  $72 \pm 4\%$  of MS stars in the  $V$  versus  $c_{U,B,I}$  CMD, and  $27 \pm 6\%$  and  $73 \pm 4\%$  of MS stars in the  $B$  versus  $(U-B)$  CMD. In the outer field (right panels) we obtained that MSa and MSbc contain respectively  $26 \pm 7\%$  and  $74 \pm 4\%$  of MS stars in the  $V$  versus  $c_{U,B,I}$  CMD, and  $29 \pm 8\%$  and  $71 \pm 6\%$  of MS stars in the  $B$  versus  $(U-B)$  CMD.



**Fig. 13.** *Top:* Radial distribution of the fraction of population ‘a’ (blue) and ‘b’+‘c’ (red) stars with respect the total number of stars. *Bottom:* radial trend of the ratio between  $f_{\text{POP}a}$  and  $f_{\text{POP}bc}$  stars. On the left we considered single radial interval for each set of data, while in the right panel we divided the radial interval in different bins. The distribution seems to be flat in both the cases.

For completeness we also calculated synthetic colors of two MS stars with the  $I = I_{\text{CUT}}$  and the same chemical composition (same abundance of light elements). We assumed for bMS primordial helium and for rMS the helium abundance of the best-fitting model. Results are represented as blue squares in Fig. 15 and confirm that the abundance of light elements assumed in the model does not affect our conclusion on the helium abundance of the two MSs, which are based on the optical colors. Instead the different CNO content strongly affect the  $U$  band.

In principle, the He content of stellar populations in GCs can also be estimated using He lines in HB star spectra (e.g. the HeI line at  $\lambda = 5875.6\text{\AA}$  line, Villanova et al. 2009, 2012; Marino et al. 2014 ). However, spectroscopic measurement of He in GC stars has many limitations. First of all, He can only be measured for stars in a very limited temperature interval ( $8500 < T < 11500\text{ K}$ ). In fact, stars with  $T \leq 8500\text{ K}$  are not sufficiently hot to form He lines, while stars bluer than the Grundahl jump (Grundahl et al. 1999,  $T \geq 11.500\text{ K}$ ) are affected by He sedimentation and metal levitation which alter the original surface abundance. The HB of NGC 6121 is populated both on the red and the blue side of the RR Lyrae instability strip. Spectroscopic investigation by Marino et al. (2011) reveals that the blue HB is made of second population Na-rich and O-poor stars, while red HB stars belong to the first population. In NGC 6121, the HB segment with  $8500 < T < 11500\text{ K}$  corresponds to the blue HB, and therefore it only provides partial information only. In this cluster (as in many others) it is not possible to spectroscopically measure the He content of the first population.

Villanova et al. (2012) have used the HeI line at  $\lambda = 5875.6$  to estimate the helium content of six blue-HB stars in the blue HB of NGC 6121. All of them are second-population stars. They derived a mean value of  $Y=0.29\pm0.01$  (random)  $\pm 0.01$  (systematic) and conclude that second-population stars would be en-

**Table 4.** Parameters used to simulate Synthetic Spectra of rMS and bMS stars and estimation of helium difference between the two population for different  $I_{\text{CUT}}$  in the case of NGC 6121

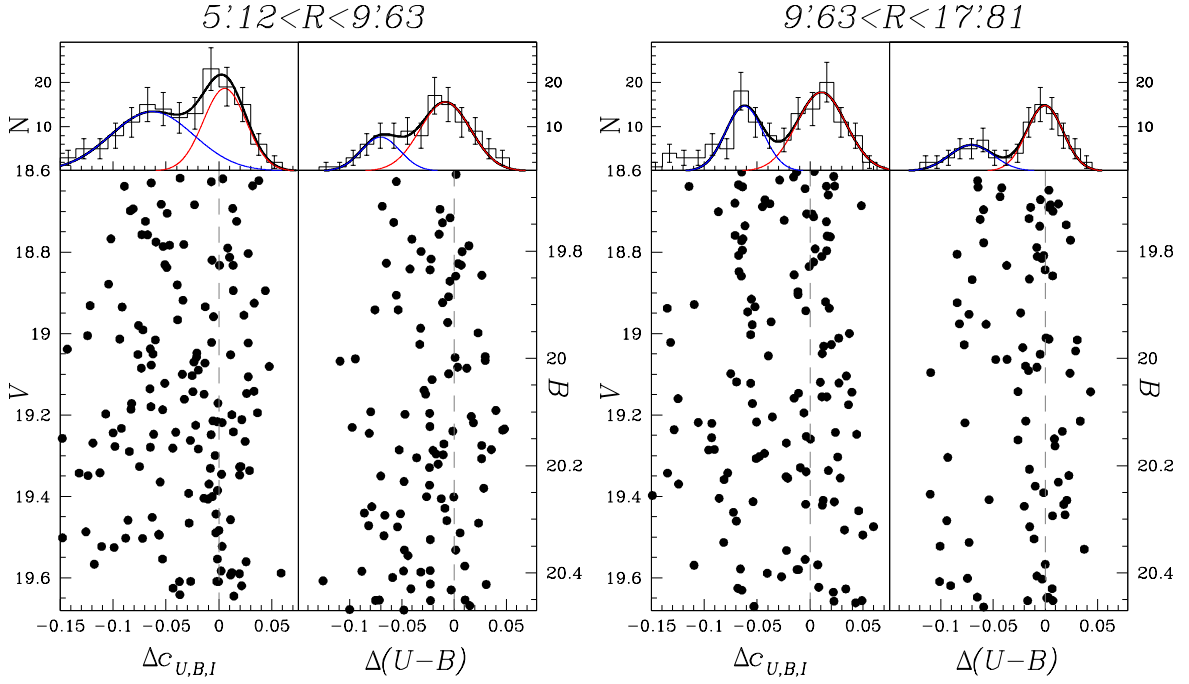
$I_{\text{CUT}}$	$T_{\text{EFF},\text{bMS}}$	$T_{\text{EFF},\text{rMS}}$	$\log g_{\text{bMS}}$	$\log g_{\text{rMS}}$	$\Delta Y$
17.3	5542	5571	4.58	4.57	0.014
17.5	5397	5444	4.60	4.60	0.021
17.7	5247	5297	4.63	4.63	0.022
17.9	5095	5149	4.65	4.65	0.024
18.1	4944	4989	4.66	4.66	0.021
average	0.020, $\sigma=0.008$				

hanced in helium by  $\sim 0.04$ - $0.05$  dex. This estimate of the He content has been made by assuming LTE approximation. However, the HeI line at  $\lambda = 5875.6$  is affected by NLTE effect, which can cause an error in the  $Y$  estimate as large as  $\Delta Y=0.10$  (see Marino et al. 2014 for the case of NGC 2808). Appropriate NLTE analysis is required to infer reliable He abundances from spectroscopy of HB stars in NGC 6121. In contrast, the He difference between red- and blue-MS stars in NGC 6121 comes from the colors of the fiducial lines, which have small color uncertainties.

## 6.2. NGC 6752

We followed the same procedure to estimate the average helium difference between MSa and MSbc stars. We measured the color distance between the two fiducial lines of MSa and MSbc in the  $I$  versus  $(X - I)$  CMDs (Fig. 16), where  $X = U, B, V$ , at reference magnitudes  $I_{\text{CUT}} = 18.55, 18.75, 18.95, 19.15$  and  $19.35$ . The color difference  $\Delta(X - I)$  at  $I_{\text{cut}} = 18.95$  is plotted in the bottom panel of Fig. 16 as a function of the central wavelength of the  $X$  filter.





**Fig. 14.** Color distribution analysis for the MSs stars of NGC 6121 in two different radial bin, containing almost the same number (754 and 755) of stars. In the inner field (left panels) we obtained that rMS and bMS contain respectively  $42 \pm 20\%$  and  $58 \pm 20\%$  of MS stars in the  $V$  versus  $c_{U,B,I}$  CMD, and  $73 \pm 16\%$  and  $27 \pm 17\%$  of MS stars in the  $B$  versus  $(U-B)$  CMD. In the outer field (right panels) we obtained that rMS and bMS contain respectively  $62 \pm 6\%$  and  $38 \pm 7\%$  of MS stars in the  $V$  versus  $c_{U,B,I}$  CMD, and  $67 \pm 6\%$  and  $33 \pm 9\%$  of MS stars in the  $B$  versus  $(U-B)$  CMD.

**Table 5.** Parameters used to simulate Synthetic Spectra of MSa and MSbc stars and estimation of helium difference between the two population for different  $I_{\text{CUT}}$  in the case of NGC 6752

$I_{\text{CUT}}$	$T_{\text{EFF,MSa}}$	$T_{\text{EFF,MSbc}}$	$\log g_{\text{MSa}}$	$\log g_{\text{MSbc}}$	$\Delta Y$
18.55	5410	5456	4.65	4.65	0.021
18.75	5254	5306	4.67	4.67	0.023
18.95	5100	5150	4.69	4.69	0.023
19.15	4946	4998	4.70	4.70	0.025
19.35	4798	4851	4.72	4.72	0.026
average					$0.024, \sigma = 0.006$

We used BaSTI isochrones (Pietrinferni et al. 2004, 2009) to estimate  $T_{\text{eff}}$  and  $\log g$  at different  $I_{\text{CUT}}$ .

We assumed that MSa has primordial helium abundance,  $Y = 0.248$ , and varied the helium content of the MSbc between 0.248 and 0.400 in steps of  $\Delta Y = 0.001$ . We assumed for the MSa the same C, N, O, Mg, Al and Na abundances of the population ‘a’ of Mi13; for the chemical composition of the MSbc we considered the average of the abundances of the population ‘b’ and ‘c’ listed by Mi13.

As mentioned above, we obtained synthetic spectra for the adopted chemical compositions, integrated them over the transmission curves of the  $U$ ,  $B$ ,  $V$ ,  $I$  filters, and computed the helium difference using the best-fitting model.

We obtained that the MSbc is helium enhanced with respect to the MSa of  $\Delta Y = 0.025 \pm 0.006$ . As for NGC 6121, since the  $U$  magnitude is affected by the abundance of light elements, we used  $B-I$  and  $V-I$  colors only to estimate  $Y$ . Note that the abundance of light elements assumed in the model does not affect our conclusion on the helium abundance of the two MSs, as already proved in the case of NGC 6121.

### 6.3. Relation between HB morphology and Helium abundance

In their work, Milone et al. (2014b) have sought correlations between HB morphology indicators and physical and morphological GC parameters. Among these parameters there is also the maximum helium difference between stellar populations hosted by GCs.

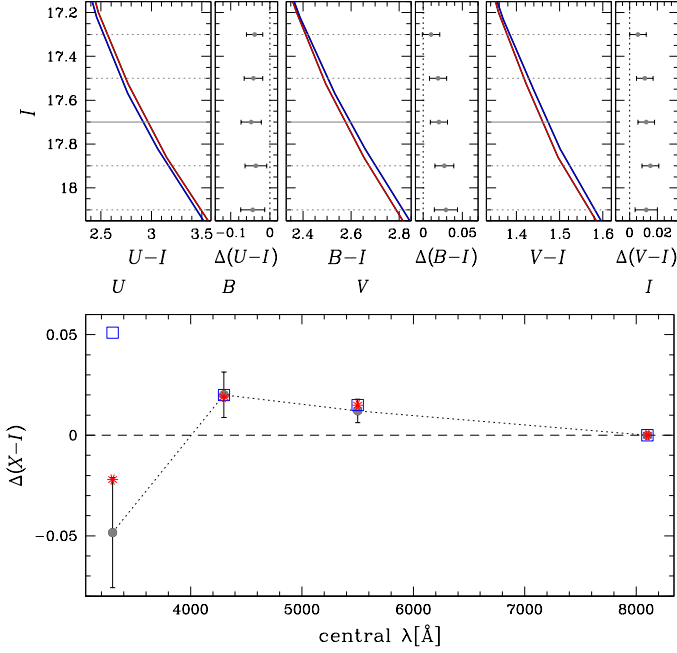
They introduced two different parameters to describe the HB morphology:  $L_1$ , that is the color difference between the RGB and the coolest border the HB, and  $L_2$ , that is the color extension of the HB (for more details, see Fig. 1 of Milone et al. 2014b).

They divided the sample of 74 GCs in three groups: in the first group, G1, there are GCs with  $[\text{Fe}/\text{H}] \geq -1.0$ ; the second group, G2, includes GCs with  $[\text{Fe}/\text{H}] < -1.0$  and  $L_1 \leq 0.4$ ; the third group, G3 contains GCs with  $L_1 > 0.4$ .

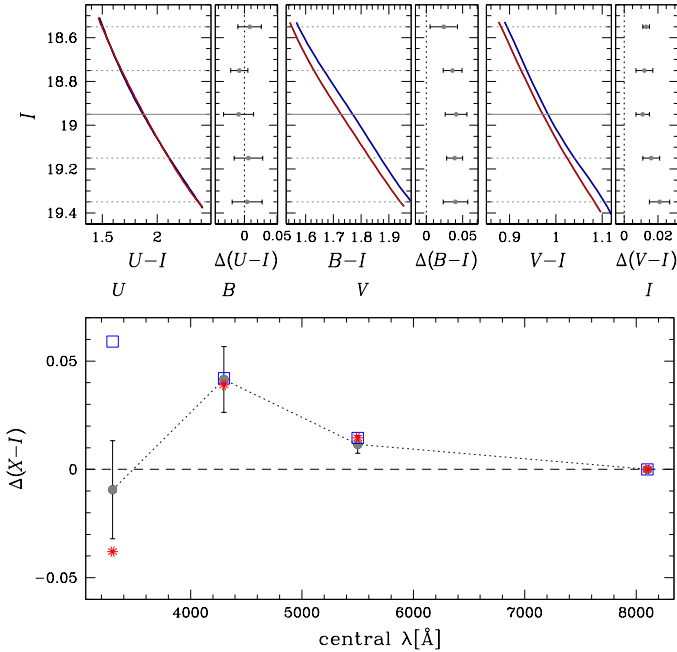
They found a tight correlation between  $L_2$  and the maximum internal helium difference ( $\Delta Y$ , measured on the MS) for the group G2+G3 (see Fig. 8 of their paper).

In our work we add two more points to their data-set, the Helium difference between the two populations of NGC 6752 and NGC 6121, as computed in this work. In the case of NGC 6752, the added point constitutes a lower limit because the Helium difference between Pop<sub>a</sub> and Pop<sub>bc</sub>,  $\Delta Y(\text{Pop}_a - \text{Pop}_{bc})$ , is the average value between  $\Delta Y(\text{Pop}_a - \text{Pop}_b)$  and  $\Delta Y(\text{Pop}_a - \text{Pop}_c)$ .

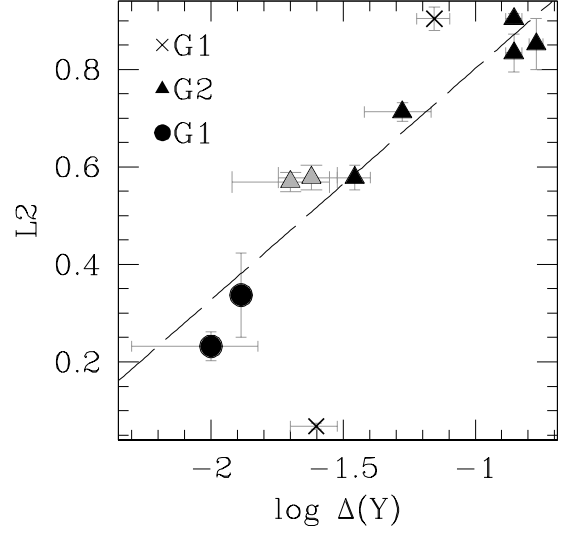
The result is in Fig. 17: in black there are the points of Milone et al. (2014b) and in grey the points added in this work. In analogy to the work of Milone et al. (2014b), the crosses refer to the G1 GCs, triangles to G2 group and dots to G3 clusters. Our data points confirm the tight correlation between  $L_2$  and  $\Delta Y$ . We found a Spearman’s rank correlation coefficient  $r_{\text{G2+G3}} = 0.93$  (to be compared to  $r_{\text{G2+G3}} = 0.89 \pm 0.17$  found by Milone et al. 2014b), with  $\sigma_{r_{\text{G2+G3}}} = 0.08$  (the uncertainty in  $r$  is estimated by means of bootstrapping statistic, as in Milone et al. 2014b).



**Fig. 15.** *Top panels:* MS fiducial in 3  $X-I$  CMDs ( $X = U, B, V$ ) of NGC 6121. The horizontal lines represent the magnitudes  $I_{\text{CUT}}$  for which the color distance between the two MSs is calculated. For each  $I_{\text{CUT}}$  the error in  $\Delta(X-I)$  is shown. *Bottom panel:*  $X-I$  color distance between rMS and bMS at  $I_{\text{CUT}} = 17.7$  as a function of the central wavelength of the  $X$  filter. Observations are represented with gray dots. Red asterisks are the best-fitting model, while blue squares are the results obtained calculating synthetic colors of two MS stars with the same light-element chemical composition, but different He content. The blue squares demonstrate that the abundance of light elements assumed in the model does not affect the results on the He abundance of the two MSs in the optical colors but strongly affect the  $U$  band.



**Fig. 16.** As in Fig. 15, but for NGC 6752. In the top panels, the fiducial blue is that one of the MSa and the red fiducial is for MSbc.



**Fig. 17.** The HB morphological parameter  $L_2$  as a function of the logarithm of the maximum helium difference among stellar populations in GCs. The black line is the best-fitting straight line for G2+G3 GCs. In black there are the data of Milone et al. (2014b), in grey the data of this work.

This result is a further proof that the helium-enhanced stellar populations are likely related to the HB extension, as predicted by theory.

## 7. Summary

The photometric analysis of ESO/FORS2 data of the external regions of the three nearby Galactic GCs NGC 6121 (M4), NGC 6752 and NGC 6397 has confirmed that the first two GCs host multiple stellar populations. Indeed, the  $B$  versus  $U-B$  and  $V$  versus  $U-B, I$  CMDs of NGC 6752 and NGC 6121 show a split of the MS in two components. Excluding the unique case of  $\omega$  Cen, this is the first time that a split of the MS is observed using ground-based facilities.

The multiple stellar populations of NGC 6397 was investigated by Milone et al. (2012a) using *HST* data. They found two stellar populations characterized by a modest helium variation  $\Delta Y \sim 0.01$ . Unfortunately, in this work, it was not possible to analyze these populations, because of the size of our photometric errors is comparable to the small color separation between the MSs.

Using *HST* data, Mi13 have already demonstrated that NGC 6752 host three stellar populations. They computed the radial trend of the ratio between the number of stars of different populations out a radial distance from the center of 6'13. Because of larger photometric errors, we have resolved only two MSs. Comparing them with the work of Mi13, we found that the less populous MS corresponds to their population 'a', while the most populous MS hosts both their populations 'b' and 'c'. In average we found that the MSa contains about 26% of the total number of stars and the MSbc host about 74% of the MS stars. The most straightforward interpretation is that the MSa is formed by stars of the first generation with chemical abundances similar to that of the Galactic halo field stars with the same metallicity; the MSbc hosts stars of second generation, formed out of material processed through first-generation stars. This population is characterized by stars enhanced in helium, with  $\Delta Y = 0.025$ . Our measurement of the helium enhancement is in agreement with the average  $\Delta Y$  of the populations 'b' ( $\Delta Y \sim 0.01$ ) and



‘c’ ( $\Delta Y \sim 0.03$ ) obtained by Mi13. We extended the study of the radial trend of the populations of NGC 6752 to more external regions, confirming the results of Mi13, of a flat distribution. Therefore we cannot confirm the results by Kravtsov et al. (2011) and Kravtsov et al. (2014); they found that the two populations show a strong gradient at a radial distance close to the half-mass radius.

In a recent work on NGC 6121, Milone et al. (2014a) investigate the bottom of the MS of this cluster using *HST* near-infrared photometry. They found that the MS splits into two sequences below the MS knee. In particular they identified two MSs: a MS<sub>I</sub> that contains  $\sim 38\%$  of stars and MS<sub>II</sub> formed by the remaining 62%. They show that the split of the MS is mainly due to the effect of H<sub>2</sub>O molecules, present in the atmospheres of M-dwarfs, on their near-infrared color, and that it is possible to associate the MS<sub>I</sub> to a first generation of stars and the MS<sub>II</sub> to a second one. Marino et al. (2008), analyzing spectra of RGB stars, found that  $\sim 64\%$  of stars are Na-rich and O-poor and the remaining  $\sim 36\%$  have chemical abundances similar to those of Halo-field stars with the same metallicity. All these results are in agreement with what we have obtained in this work: the MS of NGC 6121 splits in the *B* versus (*U* – *B*) and *V* versus *C*<sub>U,B,I</sub> CMDs. We found two MSs: a less populous MS that contains  $\sim 37\%$  of MS stars and which constitutes the first generation of stars and a more populous second generation MS that contains  $\sim 63\%$  of stars. Villanova et al. (2012), using spectroscopic measurements of blue HB (bHB) stars, obtained that the difference in helium abundance between these stars and the red HB (rHB) stars is  $\Delta Y = 0.02/0.03$ . A spectroscopic analysis of Marino et al. (2011) revealed that the rHB stars have solar-scaled [Na/Fe], while bHB stars are Na enhanced. In contrast to the results of Villanova et al. (2012), a lower constraint to the level of He enhancement is set by Valcarce et al. (2014), founding a maximum  $\Delta Y = 0.01$  between bHB and rHB stars. Analyzing how the two MS of NGC 6121 behave in different CMDs, we computed the helium abundance difference between them. Our result is  $\Delta Y = 0.020 \pm 0.005$ , in agreement with that obtained by Villanova et al. (2012). Also in the case of NGC 6121, we did not find evidence of changes in the fraction of bMS/rMS stars in the radial range between  $1.2 r_h < R < 4.1 r_h$ .

Milone et al. (2014b) found a correlation between the HB morphological parameter  $L_2$  and the maximum helium difference among stellar populations in GCs. Using the helium abundances computed in this work for NGC 6121 and NGC 6752, we confirm this correlation and the theoretical indications that helium enhanced stellar populations are responsible of the HB extension.

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